An overview of wide Band Gap Semiconductor physics of failure and reliability

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UTD (Wallace’s Group)
Purpose

• Historical overview of the main findings that have shaped our present understanding of GaN FET physics of failure:

• Where are we going. Identifying the Gap
Outline

• Introduction
• Evolution of our understanding of the physics of failure of GaN FET Technology
  – Mitigation through Surface Engineering (2008-2010)
  – Understanding the Surface (2010 - …)

• Conclusion
Introduction

- TRIQUINT’S GaN Ku-Band FET TECHNOLOGY

![Diagram of GaN FET technology]

Maximum Operation Voltage: 40V

RF: $P_{\text{Out}}$: 5.0 - 7.0 W/mm
PAE: 50% - 75%
Assoc. Gain: 10.0 dB at 18Ghz
17.0 dB at 6Ghz
Physics of Failure

• Inverse Piezoelectric Failure Model (Dec. 2005)

Electric field induced defect formation through inverse piezoelectric effect in the AlGaN Barrier

1. High $V_{DG}$ results in high field in the Drain Gate edge region

2. Through inverse piezoelectric effect, high field introduces severe strain in the AlGaN barrier

3. Piezoelectric strain adds on top of lattice mismatch strain

4. If excessive, strain relaxes during operation through crystallographic defect formation

5. Defects are electrically active and behave as electron traps

Proposed by J. del Alamo and M. Kuball
Physics of Failure

- Inverse Piezoelectric Failure Model (2006)

Marquee Experiment

- Sudden gate current degradation at very specific $V_{GD}$
- Irrecoverable degradation (light or temperature)
- Degradation even without drain current
- Scaling (Gate length, DS spacing, etc...) consistent with inverse piezoelectric effect
- Simulation model

J. del Alamo
Physics of Failure

- Inverse Piezoelectric Failure Model (Nov. 2006)

First Evidence of Mechanical Degradation

RF LifeTest. 28V, 280C

Mechanical deformation on the drain edge of the gate consistent with inverse piezoelectric theory
Physics of Failure

- Inverse Piezoelectric Model (TEM Program with UTD). 2007
  
  - Observed only the Gate-Drain edge of the device
  - Observed independent of the presence of an oxide below the gate
  - Observed only when both Voltage and Temperature are present
  - When observed, identical across the full finger
  - Observed in different platforms (Si or SiC)
  - Mechanical degradation independent of time
Physics of Failure

- Inverse Piezoelectric Failure Model (Apr. 2008)

Extensive TEM Characterization consistent with Degradation by Inverse Piezoelectric effect

Electrical Degradation consistent with Mechanical Disfiguration
Physics of Failure

• Inverse Piezoelectric Failure Model (Jun. 2009)

Successes/Limitations of this degradation Model

• MODEL SUCCESSES
  • Voltage dependence degradation mechanism
  • Off state – on state degradation strengths
  • prediction of mechanical deformation in the semiconductor

• MODEL FAILURES
  • Temperature Dependence (Activation Energy)
  • Critical Voltage / LifeTest variations across the wafer
Physics of Failure

• Improved Degradation Model. (Jun. 2009)

The dynamics of the mechanical degradation and the role of the surface in initiating it are the keys for explaining the temperature acceleration of the degradation and the intra and interwafer reliability spread.

1. Chemical Pitting of the GaN surface

2. μCracking of the AlGaN barrier through inverse piezoelectric effect

3. Propagation of the Cracking along the gate width
Physics of Failure

- Improved Degradation Model (Jan 2010)

Degradation Evolution vs voltage stress

Degradation Evolution vs Time

MIT: J. del Alamo

Degradation starts through surface pitting presence
Experiment rules out dislocation effects
Physics of Failure

• Improved Degradation Model. Surface Engineering (2009)

Experiments justification

CONTAINMENT EXPERIMENTS

• EXPERIMENT 1:
  “By thickening the GaN cap we will delay the onset of AlGaN cracking (chemical pitting)”

• EXPERIMENT 2:
  “By lowering the Al content in the AlGaN barrier we will eliminate cracking”

DEGRADATION ELIMINATION EXPERIMENTS

• EXPERIMENT 3:
  “By modifying the cleaning chemistry on the surface we can possibly eliminate pitting (initiator of degradation)”
Physics of Failure

- Experimental Results (2009)

EXPERIMENT 1: “Increasing the GaN cap”

DC LifeTest. 40V. 355C

I DMax Degradation (%)

Time (hours)
Physics of Failure

• Experimental Results (2009)

EXPERIMENT 2: “Reducing the Al content of the barrier”

DC LifeTest 40V. 355C

25% lower Al
Standard
Physics of Failure

EXPERIMENT 3: “Changing the surface chemistry and eliminate pitting all together so that cracking can not occur” (2009)

Treat A1. Treat B1

Treat A2. Treat B1

Treat A1. Treat B2

Treat A2. Treat B2

Treat B2 reduces spread and improve reliability
Physics of Failure
Improved Degradation Model. Surface Engineering (Dec 2009)

DOE
- Semiconductor Termination
- Barrier Stress
- Surface Process

RESULTS
- Original Technology
- Current Technology

No Field Returns due to Inverse Piezoelectric Effect
Physics of Failure

STATUS AT THE BEGINNING OF 2010

GOOD PROGRESS OF THE IMPROVING LONG TERM RELIABILITY
BUT LINKAGE TO OTHER RELIABILITY RELATED TOPICS

• DRIFT
  – Variation of quiescent drain current at fixed gate voltage
• CURRENT COLLAPSE
  – Reduction of available swing current from its DC counterpart.
• GATE CURRENT

WAS NOT UNDERSTOOD
Physics of Failure

• Initial Gate Current

• Gate Current can be easily reduced through surface treatments. (PreGate cleaning)

• Low Gate Current is however NOT synonym of good long term reliability. Tunneling barriers which reduce gate current are inherently unstable on long term reliability.

$I_G$ (μA/mm)

10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Process 1  Process 2

Pre Gate Cleaning Process
Physics of Failure

July 2010

IMPROVING ALL FOUR PERFORMANCE-RELIABILITY CHARACTERISTICS REQUIRES NOT JUST A MITIGATION APPROACHES, BUT A REAL UNDERSTANDING OF THE SURFACE

THE REAL GaN SURFACE IS NOT WHAT WE PUT IN OUR PHYSICAL SIMULATORS
Physics of Failure

- WHAT MAKES GaN A DISRUPTIVE TECHNOLOGY (LARGE BAND GAP) MAKES IT ALSO MORE SENSITIVE TO THE SURFACE

- Surface states in GaN performing the role of Doping in GaAs
- Wide Band Gap Material tend to have slower traps
- Gate Recess difficult in Wide Band Gap Material
- Piezoelectric Sensitivity to stresses
Physics of Failure

• Understanding the surface (Sep. 2010)

APPROACH. PROCESS SIMULATIONS

- Out of the Box
- Surface Clean
- Simulated Ohmic Anneal
- Nitride Deposition
- Trunk Etch
- Clean 1
- Clean 2

- Surface Bond Analysis
- 2D Channel Charge
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- 2D Channel Charge

22/27
Physics of Failure

- XPS: X-Rate based Photoelectron spectroscopy (Surface)

- Excitation of Core electrons (well defined energies)
- Surface Sensitive

- Lehighton (Contactless resistivity)
Physics of Failure

• Evolution of Surface through the process

• Oxides
  • Evidence of oxygen below the gate on fresh devices and in the regions with strong lattice deformation on degraded devices
  • Different oxidation rates for Ga and Al can explain the GaN cap thickness dependence on current collapse and reliability

• Fluorides and Chlorides
  • Nitride trunk etch chemistry. Halogen highly reactive

• Carbon
  • Deep trap in GaN

• Others
  • Na, …
Physics of Failure

• Understanding the Surface
  – Survey
Physics of Failure

• Understanding the Surface
  – Survey

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ga %</th>
<th>N %</th>
<th>Al %</th>
<th>O %</th>
<th>C %</th>
<th>F %</th>
<th>Na %</th>
<th>Cl %</th>
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</thead>
<tbody>
<tr>
<td>Out of the Box</td>
<td>44.5</td>
<td>37.2</td>
<td>1.6</td>
<td>7.7</td>
<td>8.4</td>
<td>0.6</td>
<td>0.0</td>
<td>0.0</td>
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<td>Anneal</td>
<td>40.5</td>
<td>35.5</td>
<td>1.6</td>
<td>14.7</td>
<td>7.0</td>
<td>0.4</td>
<td>0.0</td>
<td>0.2</td>
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<tr>
<td>SiN etch</td>
<td>30.3</td>
<td>24.7</td>
<td>2.1</td>
<td>17.7</td>
<td>7.6</td>
<td>16.8</td>
<td>0.8</td>
<td>0.0</td>
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<tr>
<td>Ash</td>
<td>34.5</td>
<td>23.3</td>
<td>1.9</td>
<td>18.4</td>
<td>4.5</td>
<td>16.2</td>
<td>1.2</td>
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<tr>
<td>DIW</td>
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<td>31.5</td>
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<td>18.3</td>
<td>8.1</td>
<td>2.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

• O is picked up at annealing and no further process seems to do anything to remove it.
• F is picked up at trunk etch and is not fully removed
Conclusions

- Long Term Reliability, Drift and Current Collapse, and Gate current all are strongly dependent on the state of the semiconductor surface.

- The GaN attribute that makes this technology disruptive (its large band gap) makes reliability improvements more complicated.

- TriQuint and its University partners proposed the universal mechanisms of failure of GaN FET technology (inverse piezoelectric effect. Large TEM program). These days were heavily involved in a large comprehensive surface analysis program involving again several Universities. The goal is an improved technology based on a better understanding of its surface. We expect to be the leaders here too.